Application of pulsed power driven plasmas to study astrophysical jets and supersonic outflows

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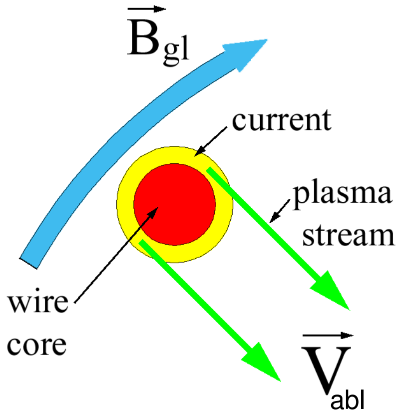
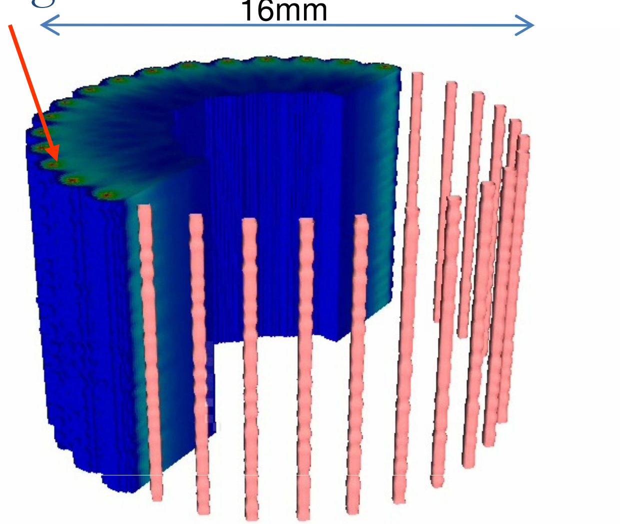
Introduction

- Mass ablation rate described by Rocket model
  (S.Ledebev, Phys Plasmas, **8**, p3734, (2001))



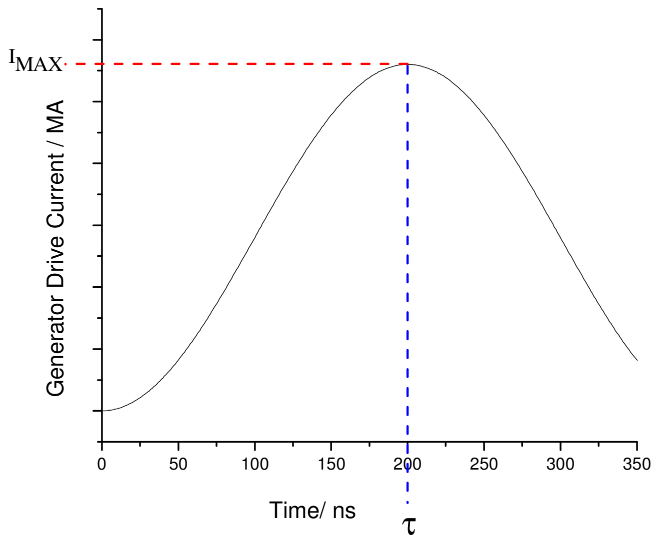
$$\boxed{V_{abl}\frac{dm}{dt} = -\frac{\mu_0 I^2}{4\pi R_0}}$$

Ablating wires



Time-slice from 3D Resistive MHD Gorgon Code
(J.Chittenden, Plasma Phys Control Fusion **46**, B457 (2004))

- Mass ablated determined by I_{max}
- Timescale determined by τ



Generator	Location	I_{max}	τ
MAGPIE	Imperial College	1MA (2MA)	250ns
GenASIS	UCSD	0.25 MA	150ns
X-Pinch Driver	UCSD	0.08 MA	50ns

Supersonic Plasma Flow

Flow Parameters

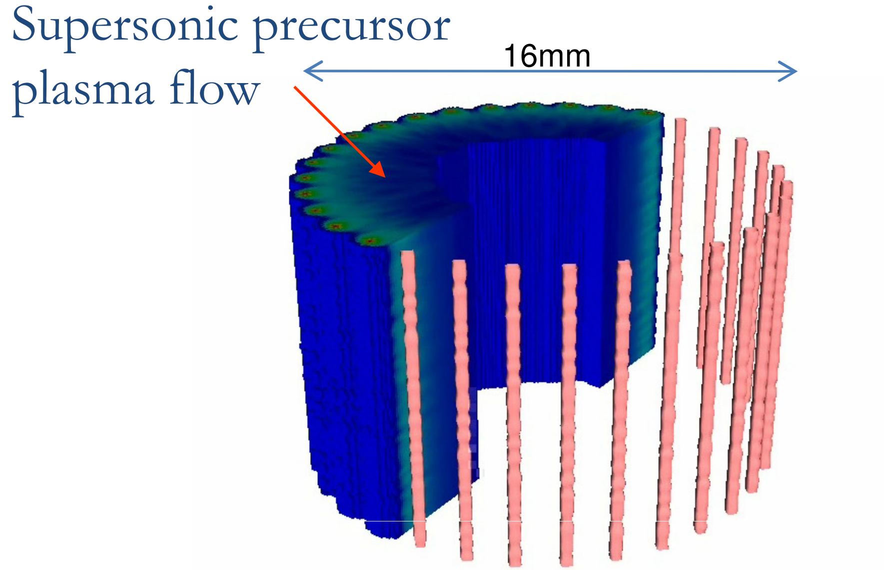
- Plasma density (N_{ion}): 1×10^{14} - $5\times10^{17}\,cm^{-3}$
- Plasma Velocity: $1.5\times10^5\ ms^{-1}$
- T_e = 5-15 eV
- Mach number: 3-5
- $R_m < 1$ (experimental)

Collisionality

$$\lambda_{perp} = \frac{m_{ion}^2 v_{abl}^4}{8\pi Z^4 e^4 n_{ion} \ln\Lambda\sqrt{\pi/2}}$$

MAGPIE
Al : typically <1mm
W : >8mm for ~140ns

UCSD:
Some collisionless flow even for Al



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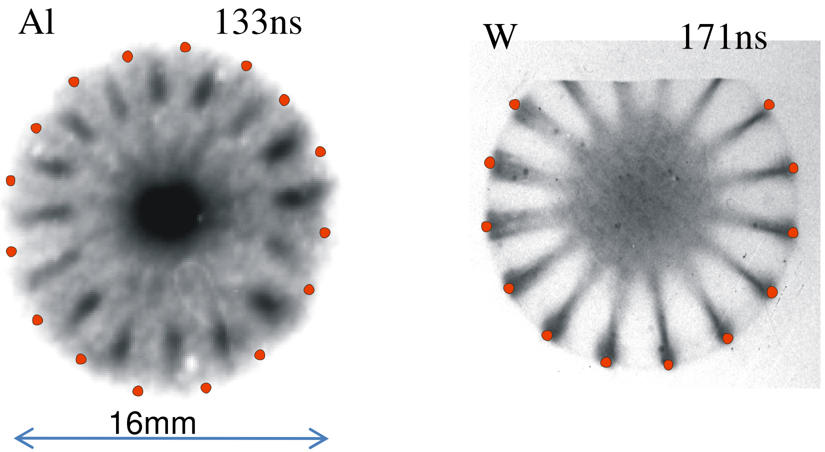
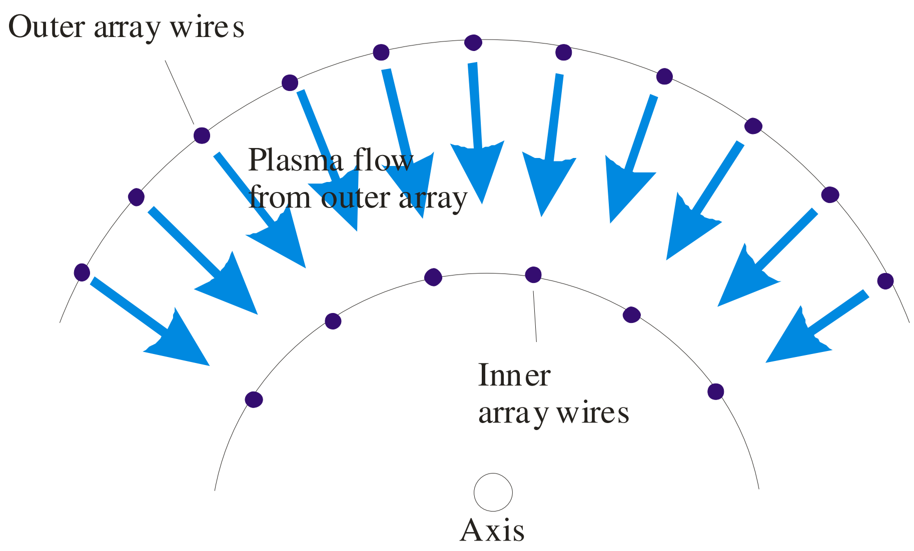


Gated axial XUV self-emission images from 16 wire arrays on MAGPIE

Shock formation in supersonic plasma flow

Collisional systems:

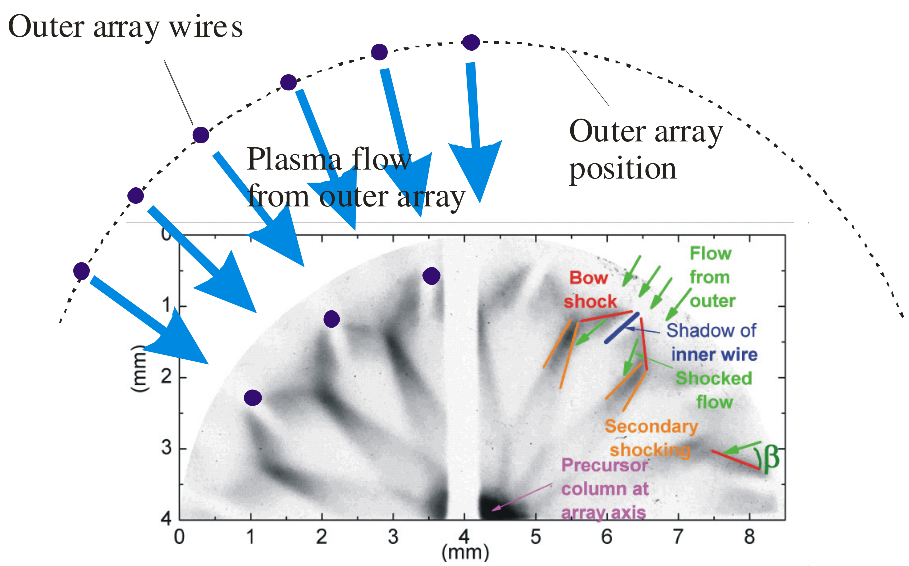
- e.g. Nested Wire Arrays at >1MA



Shock formation in supersonic plasma flow

Collisional systems:

- e.g. Nested Wire Arrays at >1MA
- Data from 32 outer and 16 inner Al wires on MAGPIE
- Bow shocks formed around inner wires
- Secondary shocking also observed
- D.J.Ampleford at HEDLA



Axial gated XUV self-emission imaging of nested Al arrays on MAGPIE
(D.J.Ampleford in prep. PRL)

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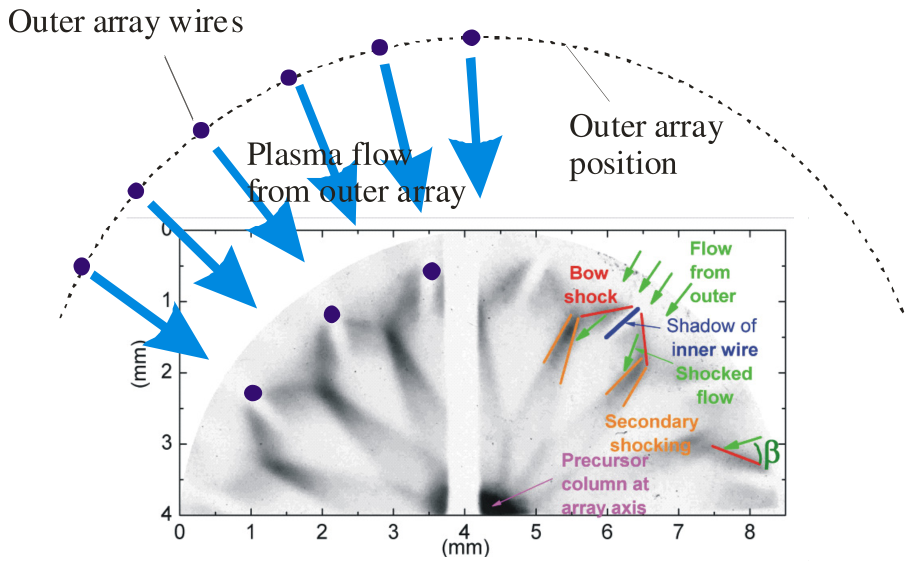
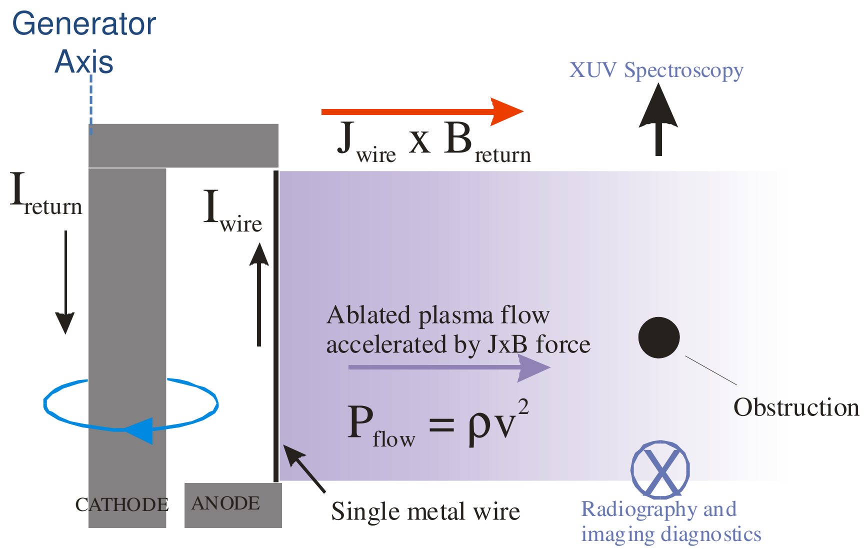


Axial gated XUV self-emission imaging of nested Al arrays on MAGPIE (D.J.Ampleford in prep. PRL)

Collisionless systems:

- UCSD experiments will provide collisionless flow,
- E.g. Laser driven experiments by Bell *et al* Phys Rev A, **38**, p1363 (1998)
- Good diagnostic access and shot rate

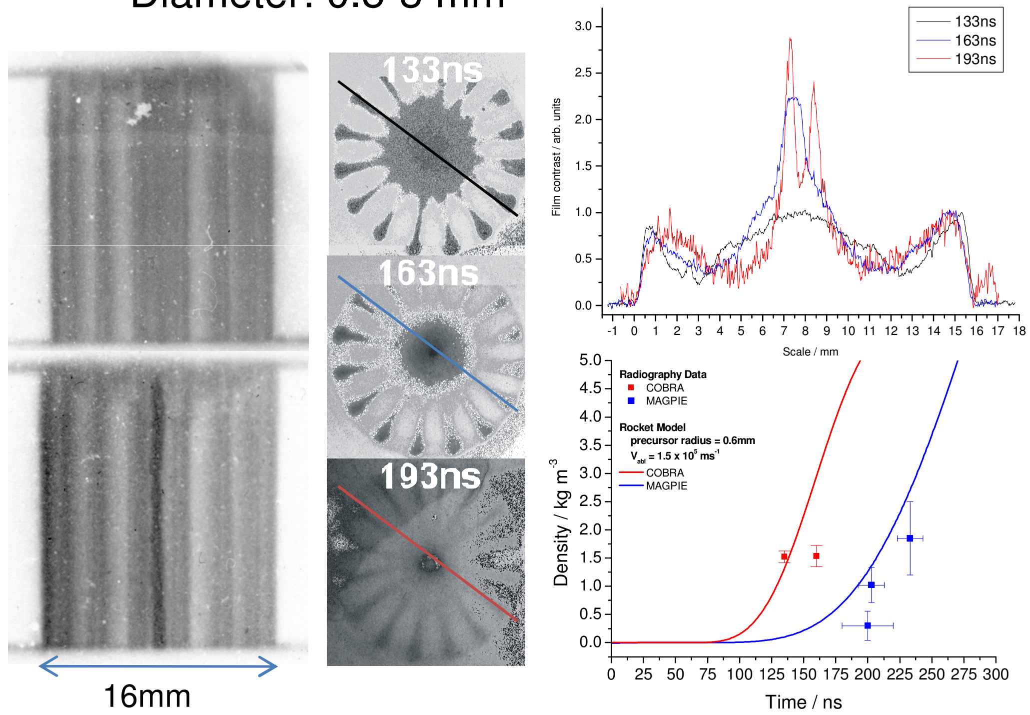


Inertially Confined plasma column formed

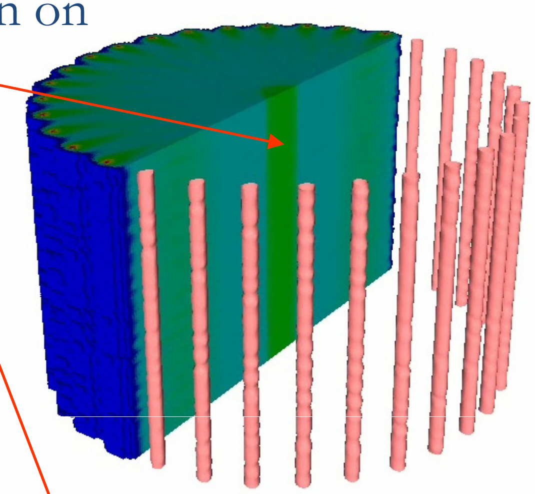
Precursor Column parameters

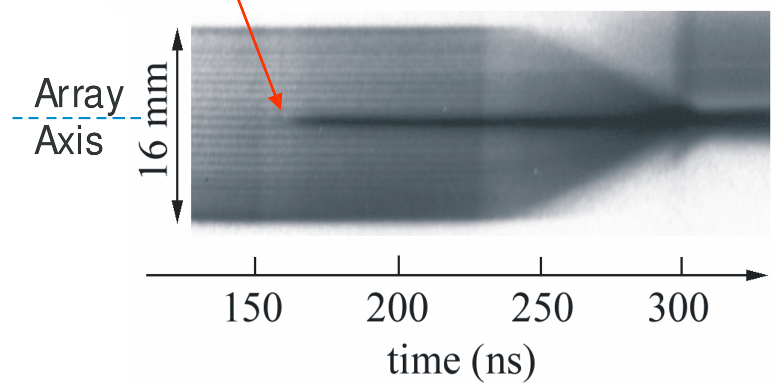
- N_{ion} : 10^{18}-10^{22} cm^{-3} (0.1 – 1 kg/m^3)
- Z: (Al) ~7, (W) ~ 14
- T_e ~ 60eV – 100 eV
- Diameter: 0.5-3 mm

Dense precursor condensation on axis



Axial (lineouts right) and radial gated XUV self-emission images, along with column density with time for MAGPIE and COBRA W experiments (Bott et al, Phys Rev E, **74** 046403 (2006))



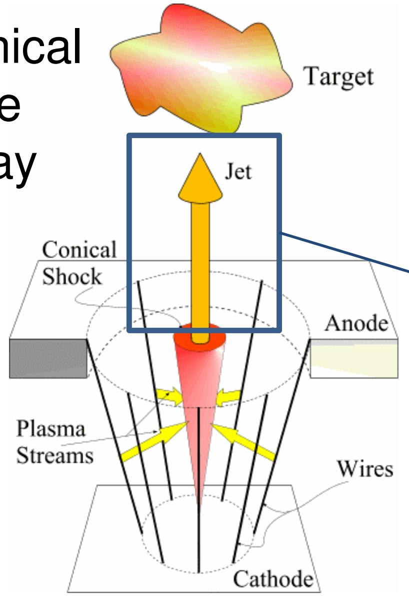


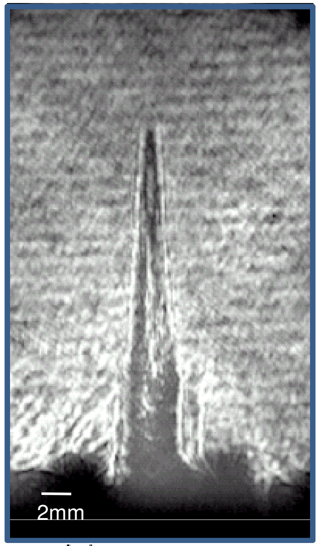
Optical Streak Photograph from MAGPIE of 32 wire Al array

Radiatively cooled and steady state (several shock transit times)

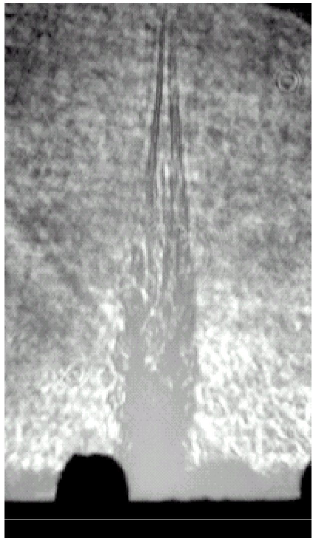
Hydrodynamic Jet formation

Conical Wire Array





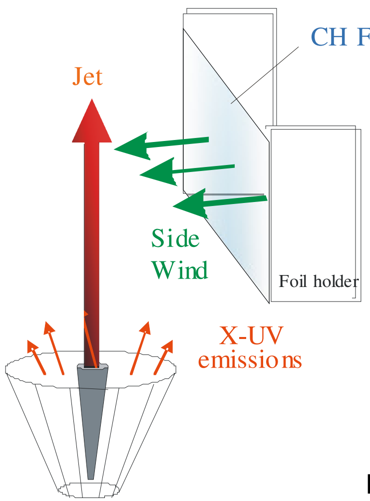
(a) 313 ns

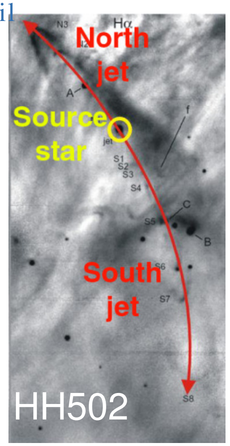

(b) 343ns

S.Lebedev et al, ApJ **564**, p113 (2002)
S.Lebedev et al, ApJ, **616**, p988 (2004)

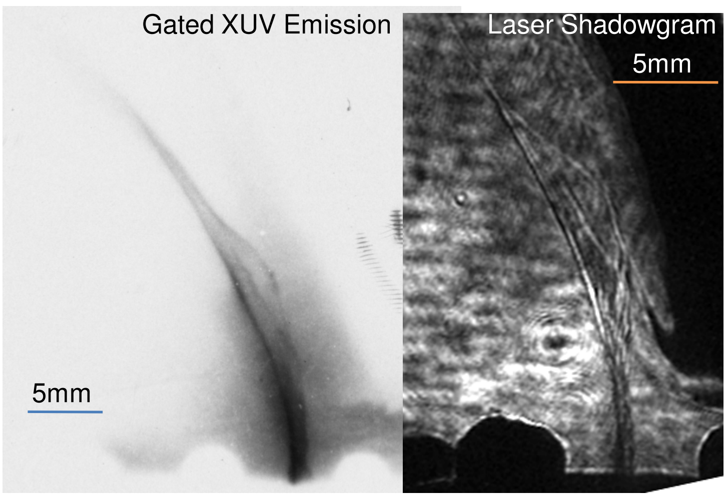
Typical Parameters scale well to astrophysical jets

General flow variables	
Length (cm)	2
Width (cm)	0.1
Dynamical time Scale	100ns
Electron temperature (eV)	10
Jet tip velocity (km/s)	~200
Jet density, → (g/cm^3)	10^{-4}
Validity of fluid description	
Localisation parameter	10^{-4}
Reynolds Number (R_e)	$10^5 - 10^8$
Peclet number (P_e)	$2 - 2 \times 10^3$
Jet scaling	
Mach number, M	> 20
Density Contrast,	100/ ~ 1
Cooling Parameter,	1

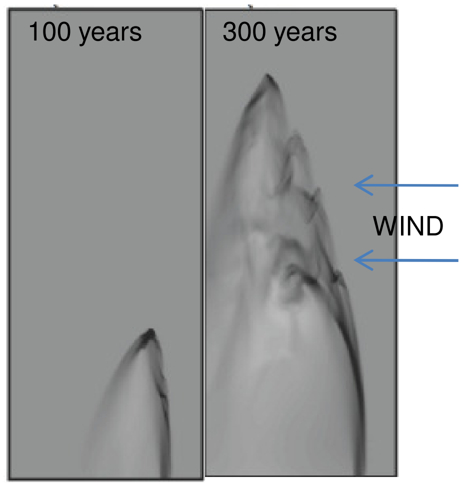




Bally & Reipurth. ApJ, **546,** p299 (2001)



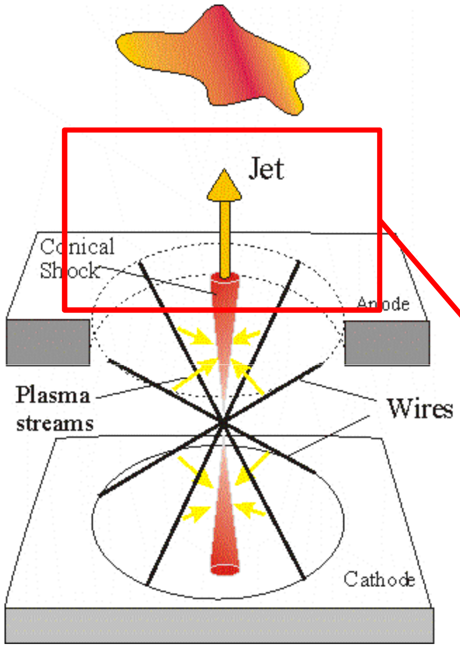
Internal shock structure during deflection
D.J.Ampleford, Astro & Space Sci , **307**, p29 (2007)

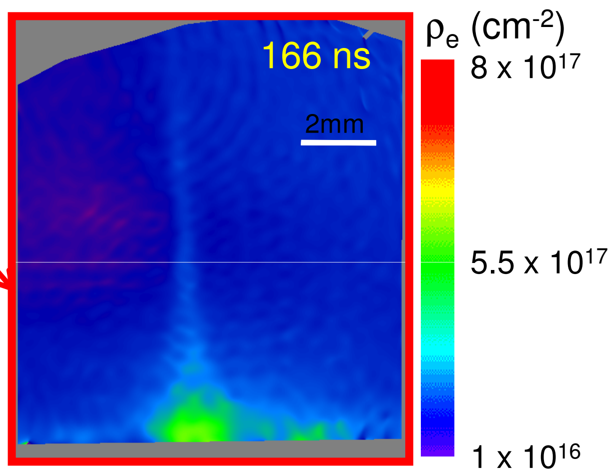


Ciardi *et al*, ApJ (accepted)
A.Frank, Astro. Space Sci , **298**, p107 (2005)

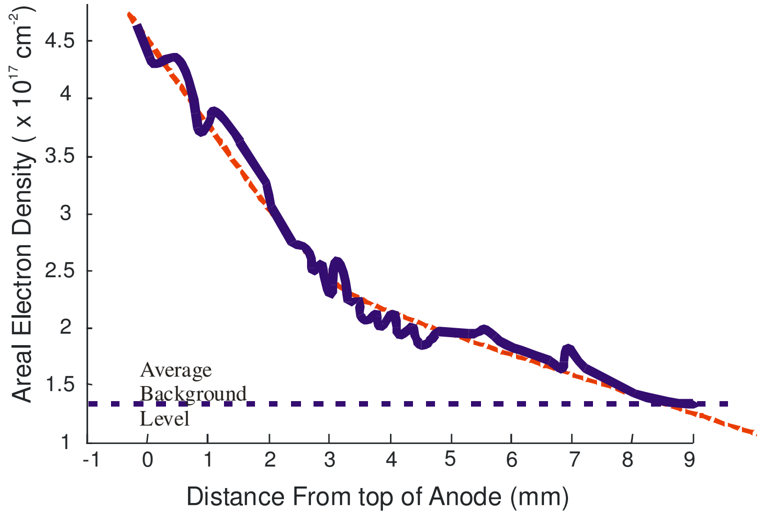
Variation of jet parameters: Jets at UCSD

- Range of jet parameters possible using different currents (e.g. 2 Generators at UCSD & MAGPIE)
- First free propagating jets from x-pinches recently measured at UCSD at 80 kA





D.M.Haas at APS 2007, and in prep. APL

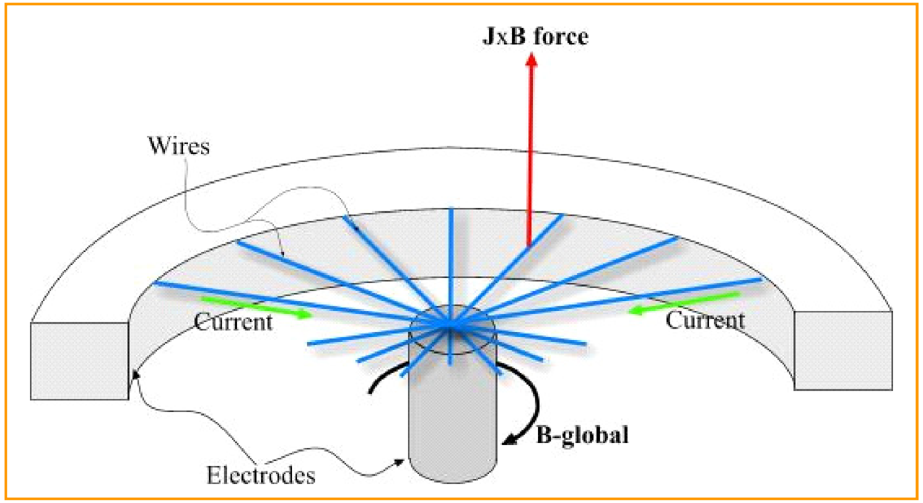


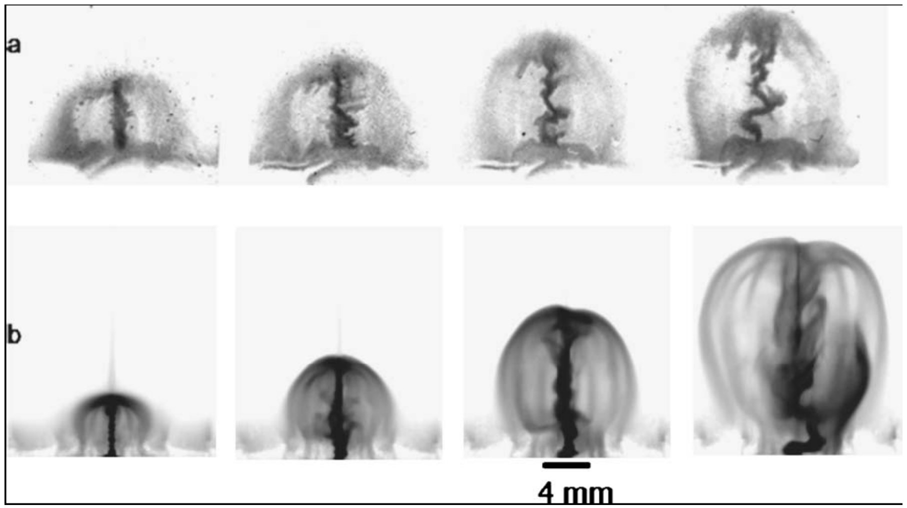
Parameter	80 kA X-pinch measured	250 kA Conical Expected (HEDLA)
V_{jet}	3.3 x 10^4 ms^{-1}	1 x 10^5 ms^{-1} (100 km/s)
c_s (radial exp)	5.5 x 10^3 ms^{-1}	
M	4-8	M > 10
ρ_e (cm^{-3})	few x 10^{17}	~ 10^{18} - 10^{19}
T (eV)	~15	~15
Z	~5	~ 5

Magnetically Driven Jets

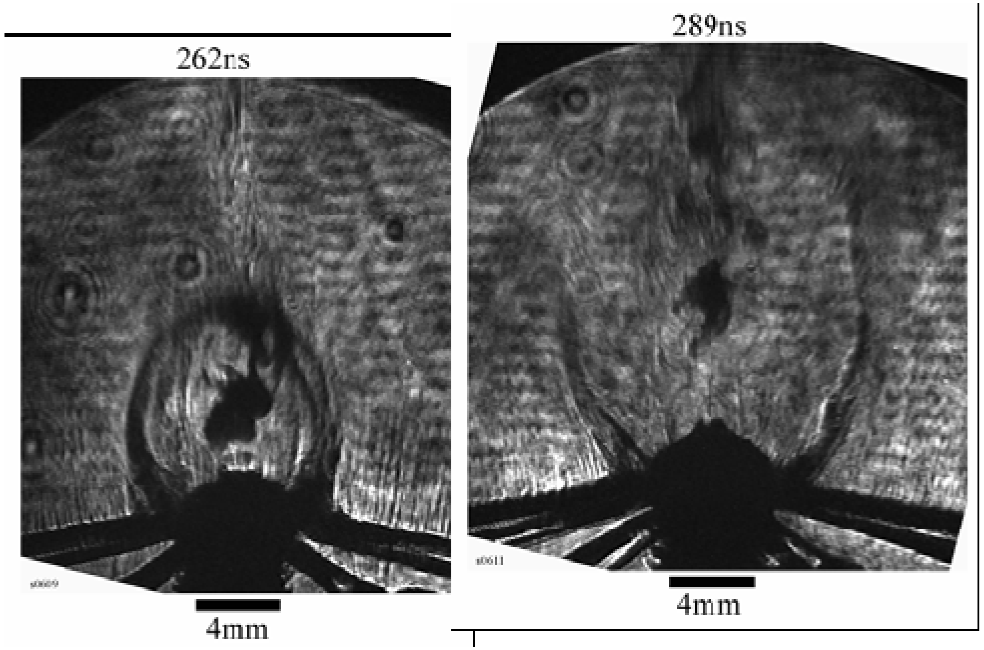
Radial Wire Arrays

- Wires show magnetic bubble structure and jet formation (Lebedev AIP Conf. 2006)
- Foils loads show repeat formation of this structure during one current pulse
- Recently foils performed with and without a gas fill (see F.Suzuki-Vidal at upcoming HEDLA conference)





Ciardi *et al*, Phys. Plasmas **14, 056501 2007**



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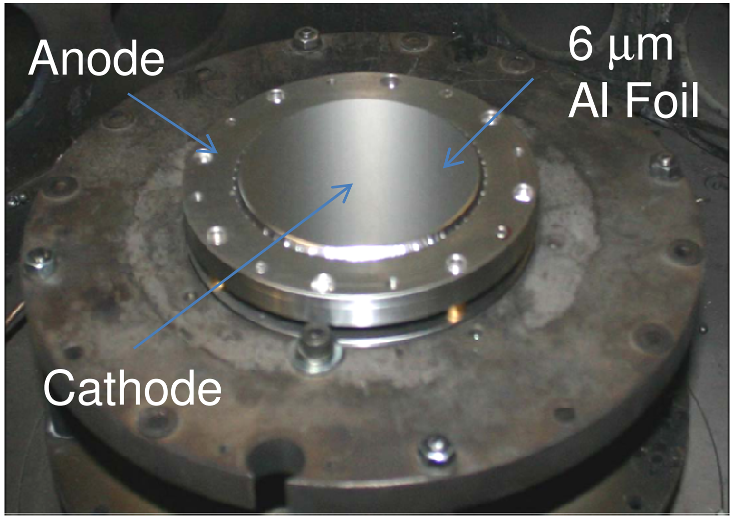

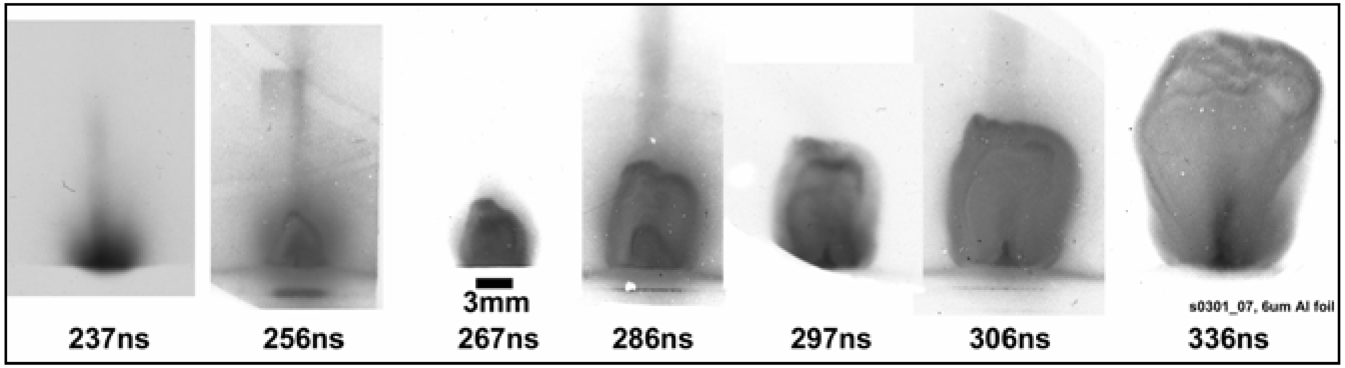

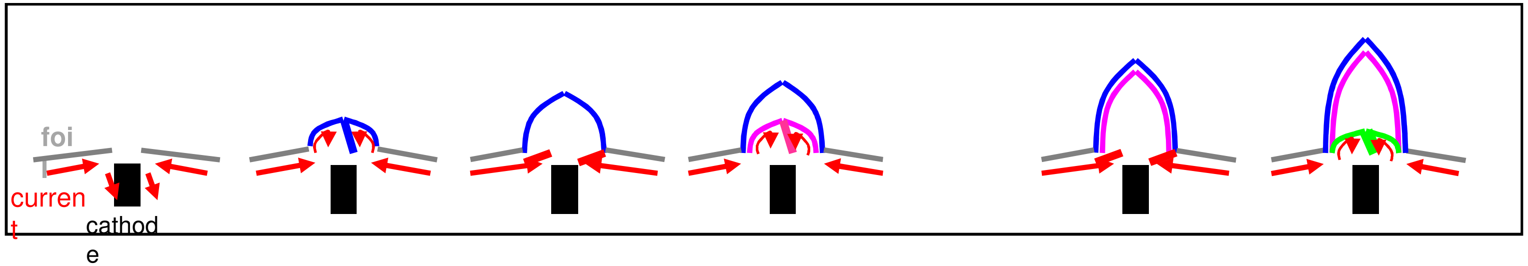

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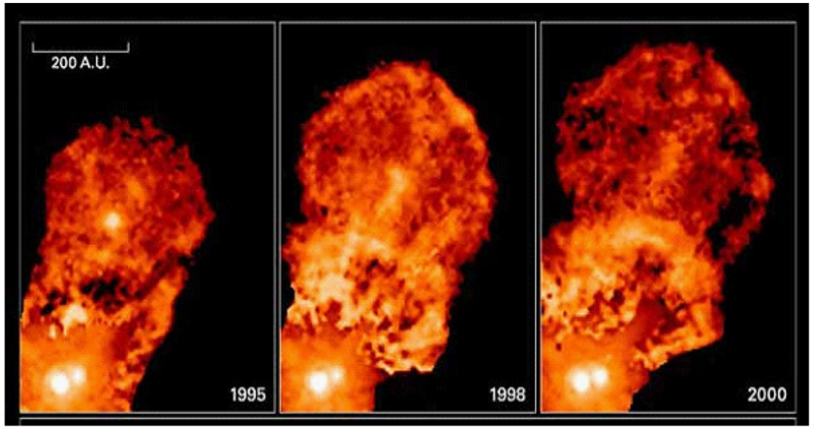
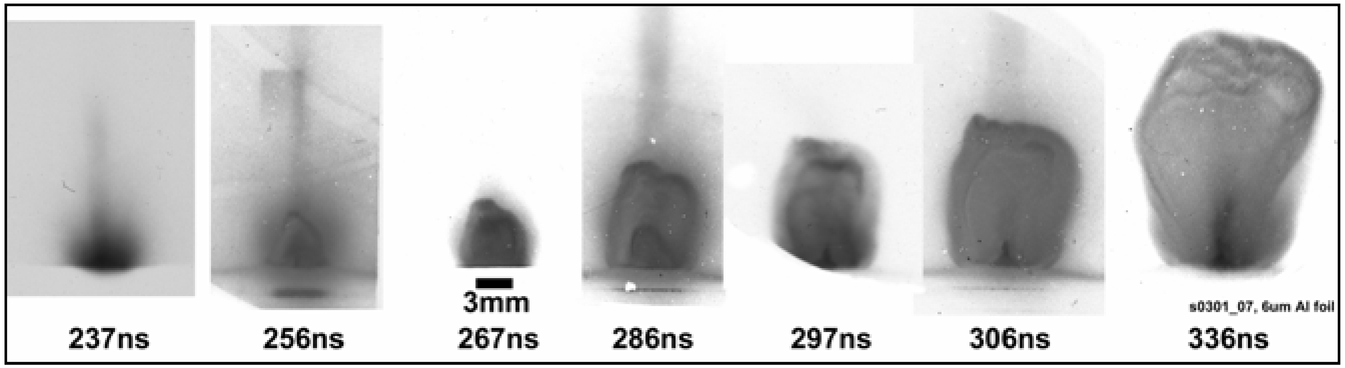
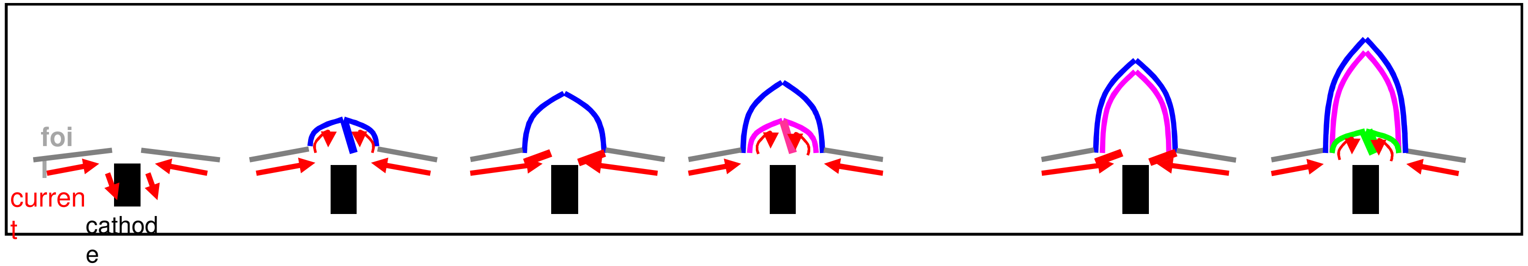


FIGURE 2a. XZ TAU. Credits: John Krist (STScI) et.al. WPFC2, HST, NASA





Future Studies at UCSD

UCSD Drivers

- Good diagnostic access, high shot rate
- 2 generators to give plasma source, and independent B-field or second plasma

Parameter space accessible

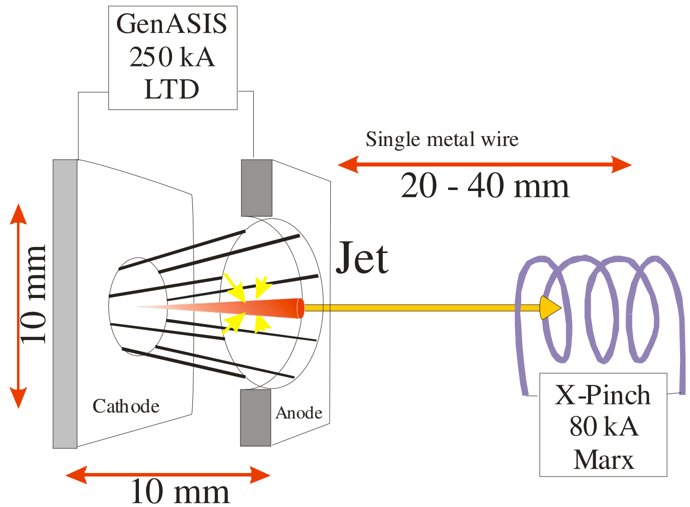
Can adjust Plasma ρ : n_{ion} ~10^{14} – 10^{17} cm^{-3}
B-field: Variable up to ~50T (200 kA)

Difficult to adjust: Plasma velocity (ablation physics)
T: 10eV in flow, 60-100 eV in column
Material At No. below 6(C) (typ. 13, Al)

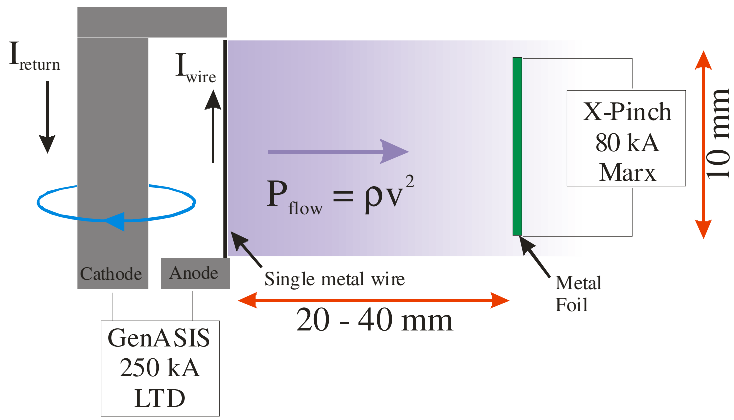
Physical Conditions: Collisionality of flow
Magnetization of ions
Low T limits plasma to low β
Need to investigate application to cosmic shocks (Drake PoP 2000)

Modelling

- GORGON for hydro and magnetic jets (J. Chittenden & A.Ciardi)
- Also use of LSP, h2d, and ePlas at UCSD



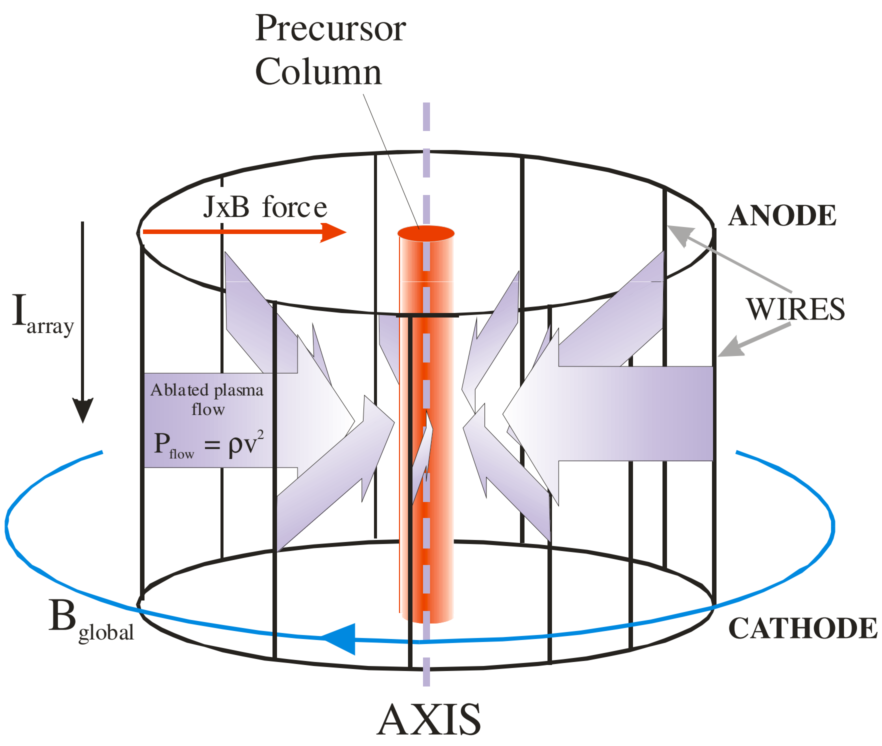
Jet propagation into B-field



Kinetic compression of exploding foil

Imperial College / UCSD Collaborative Studies

Imperial College: High current drive, extensive diagnostics, experienced team
UCSD: 2 drivers, high shot rate in simplified set-ups



Compression of targets using ablated plasma flow

Pressures: 1 – 100 kbar

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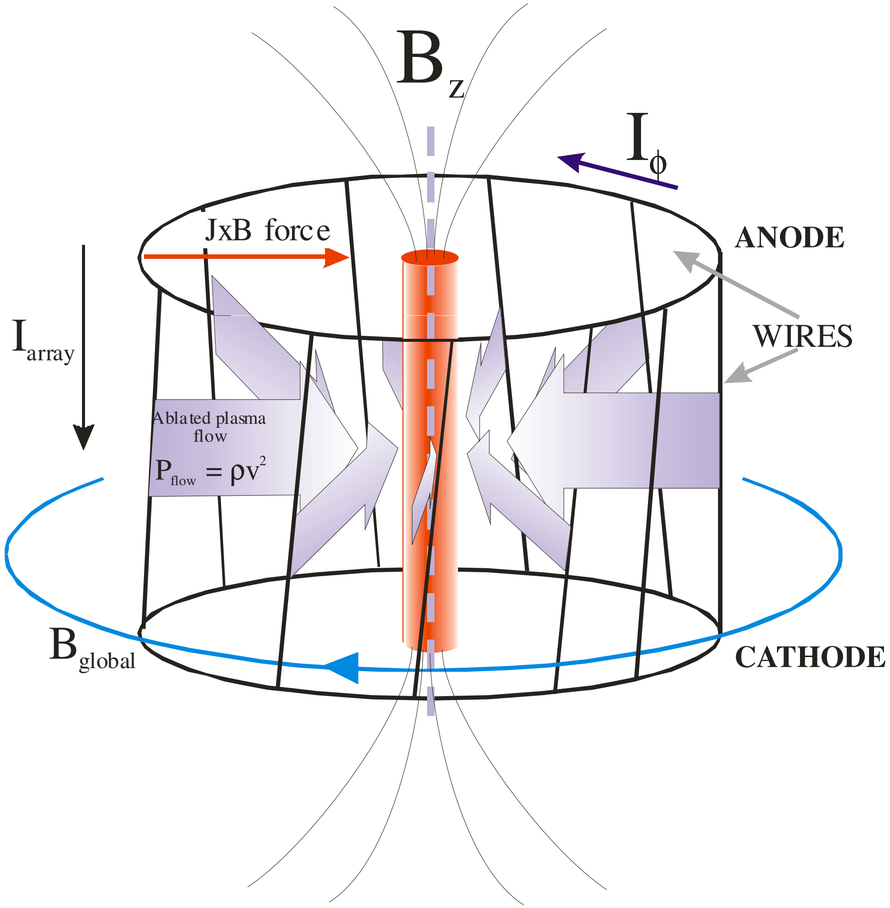

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Magnetic field in precursor column

Twisted Arrays

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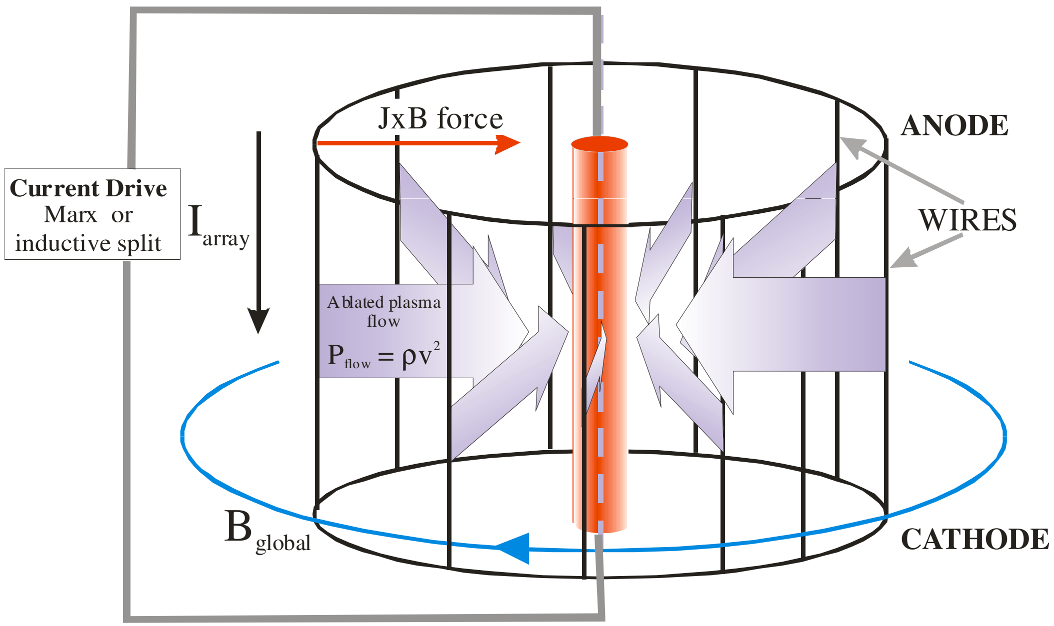

Compression of targets using ablated plasma flow

Pressures: 1 – 100 kbar

Magnetic field in precursor column

Twisted Arrays
Inductive split from main current
Additional generator

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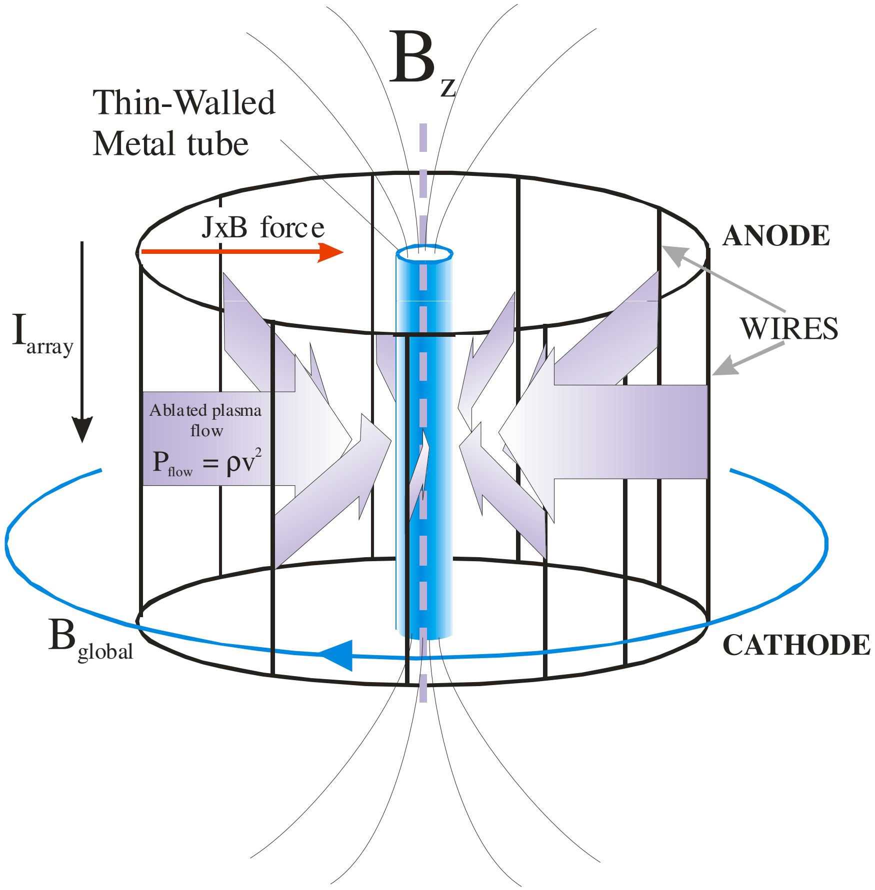

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B-field flux compression

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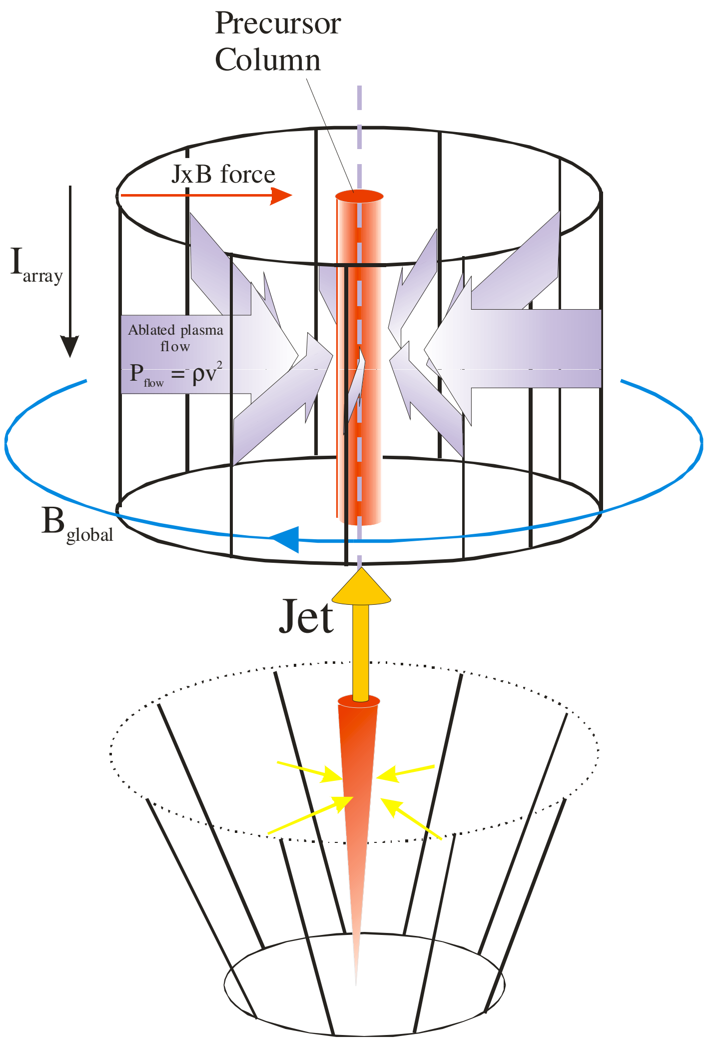

Jet Interaction Experiments

Use of radial / conical arrays for interaction with

Precursor plasma column

Magnetised precursor

Counter-propagating jet

Jets and outflows from pulsed power driven plasmas

Well characterised……

- Generation and deflection of hydrodynamic jets
- Generation of magnetically driven jets

Systems developing…..

- Multi-stage magnetically driven jets
- Low jet/ambient medium density ratio experiments
- Hydro Jet work at UCSD
- Jets with angular momentum (Ampleford, PRL **100**, p035001, 2008)

To come……

- Compression of magnetised plasmas
- Propagation of plasma into B-field / magnetised targets
- Collisionless shock systems